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Benefits of Optical Subnets in WDM Ring Networks

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Abstract: In this paper we propose the concept of optical subnets in WDM rings. By strategically placing few WDM optical add-drop multiplexers (OADMs), interleaved with many passive nodes, this hybrid ring can perform as well as a conventional OADM ring. The section of the ring between two given OADMs is called an optical subnet, while the OADM itself is called a wavelength gateway. We show analytically as well as through simulation that the capacity is still almost comparable to the case with only WDM OADMs, while the cost involved is greatly reduced. The architecture termed as optical subnets has salient features of low cost and good throughput.

I INTRODUCTION

WDM is a key technology in enhancing the network bandwidth at the optical layer. The topology in which WDM systems are used plays a key role in determining the extent to which the WDM network is utilized. Ring topologies are most common in today's networks. Wavelength reuse is one of the key benefits of WDM networking in rings. WDM add-drop units serve as network elements on the periphery of such optical rings. By using WDM add-drop equipment at each network element (node) the entire composite signal can be fully de-multiplexed into its constituent channels and switched (added/dropped or passed through). A generic WDM network element is built of multiplexers / de-multiplexers, switching matrix, set of transponder cards pre and post-line amplifiers in addition to some customized components. The number of transponder cards associated with each node is proportional to the net traffic added and dropped at that node. The cost of total number of transponders is thus dynamic. The main cost in the network is the multiplexer/ de-multiplexer and switching matrix. The theoretical upper bound on capacity of a WDM ring network is the product of number of wavelengths (assuming equal bandwidth per wavelength) and the number of nodes in the ring. However, this capacity can never be utilized because the average length of lightpaths [1] is generally greater than one hop. In other words, there are a sizable number of lightpaths for the establishment of which, WDM nodes need to configure their switches in pass-through mode. The practical capacity of a WDM ring is the product of number of wavelengths (bandwidth) and number of nodes divided by the average hop distance for all the lightpaths at a given time. This is a dynamic quantity with variation proportional to the traffic matrix. The system is under-utilized due to this offset in capacity. At a WDM network element, it is the switches (generally 2x2 per channel) which facilitate wavelength reuse by spatially separating two lightpaths on the same wavelength by positioning in the cross state. In [2] it was seen that there was a numerical limit to the number of lightpaths that could be set up on a single wavelength in a 2-fiber ring. For most practical networks where N is the numbers of nodes in the ring varying from 6-14, the number of lightpaths that could be set up on one wavelength is on average 2.43. This result proved the redundancy of multiplex and demultiplex sections as well as switches on each and every node in the ring. Due to the dynamic variations in traffic and the random distribution of length of lightpaths, it is difficult to predict the pure pass-through (transit) nodes and their placements. In this paper we attempt to address the issue of maximizing the system throughput with a new economical network topology. The network is divided into 'optical subnets', which are 'guarded' from each other using 'wavelength gateways'. This paper is divided as follows: section II describes the concept of optical subnet and wavelength gateways, section III describes the simulation model, section IV shows the analytical model to calculate the system degradation with respect to a conventional network, section V discusses the results of simulation.

II OPTICAL SUBNET: SYSTEM DESIGN

In [3] Slauze et. al. demonstrated a transparent ring network where peripheral nodes in the ring were constructed of 2x2 couplers and the cost of such nodes was low. In [4] Takeguchi et al demonstrated a unique combining and distributing amplifier inherently built of passive elements for dynamic OADM configuration. The passive node comprised of distributing and combining amplifier in addition to a set of acousto-optic tunable filters transverse to the signal flow. The passive node was used as a network element without wavelength reuse (as it lacked a switch to spatially separate two lightpaths). A single hubbed-ring network formed with any of the two proposed configurations proved to be a very low cost alternative, but was limited in capacity to λ_{max} the total number of wavelengths. The network could not deploy wavelength reuse on account of the passive node architecture. The spectrum of optical WDM ring networks thus has two extreme components, a low-cost passive network element with less system capacity and a high-cost conventional WDM OADM based network with excess system capacity. The prior needed more capacity while the excess capacity of the latter could never be utilized. We propose a subnet configuration, which essentially divides the ring logically into optical subnets. Each subnet consists of a number of passive nodes. A conventional WDM OADM demarks two subnets from one another. Fig. 1 shows a typical ring network with optical subnets internally comprising of passive low-cost nodes, and WDM OADMs between any two subnets. Inside a subnet, the fiber(s)

acts as a shared medium. The OADM dividing two subnets breaks the spatial continuity between the two-shared mediums. Between any two OADMs are a number of passive nodes. The OADM can be viewed as a wavelength gateway on account of the spectral reuse available at the point of presence. For a given network the number of subnets needed depends on the maximum capacity of each node. Though network traffic is dynamic and hard to predict, the number of transponder cards needed at each node to provision lightpaths makes the upper bound on traffic an estimable quantity on account of the offline nature of demands. Let $(Tr_i)_{max}$ be the upper bound on traffic (in lightpaths) emanating from node 'i' and $(\acute{O}Tr_i)_{max}$ be the cumulative maximum traffic in the ring. Further if the total number of wavelengths (assuming equal channel spacing) is λ_{max}, then the maximum number of subnets is given as $S_{max}= (\acute{O}Tr_i)_{max}/\lambda_{max}+1$.
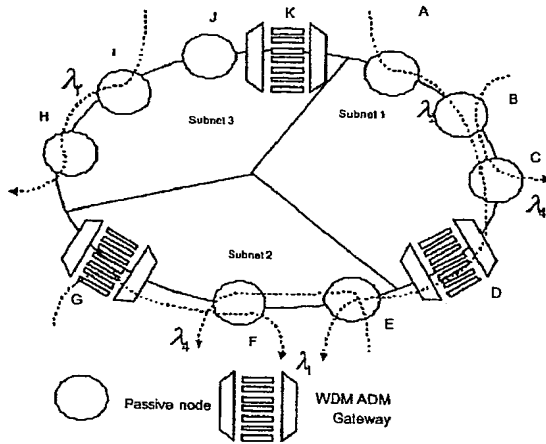

Fig. 1. Shows a 3 subnet ring configuration

Algorithm:
Initialize $j \leftarrow 1$; $t \leftarrow 1$; $sum \leftarrow 0$
    for i=1:N
        sum=sum+cap(N_i)
        if sum>=λ_{max}
            subnet(j) = node(t....N_{i-1})
            sum $\leftarrow$ 0;
            j=j+1
            t $\leftarrow N_i$
        elseif i=N & j>1
            subnet(j) = node(t...N)
        end
    end

The algorithm above gives the nodes in each subnet as well as the total number of subnets. Consecutive nodes that have a cumulative bandwidth requirement approximately equal or slightly less than the total available bandwidth (in lightpaths) are grouped together into one subnet. The last node of each subnet is a WDM OADM (wavelength gateway). Moreover for an arbitrary network the last subnet may not be as heavily loaded as the other subnets (though this is a deficiency in the network, it serves as a good load balancing approach for hubbed traffic)

Two kinds of lightpath establishment deserve attention, intra-subnet lightpath establishment and inter-subnet lightpath establishment. The wavelength assignment algorithm [5] maximizes wavelength reuse. It also assigns wavelengths heuristically such that all intra-subnet (ingress and egress nodes in the same subnet) lightpaths are assigned on the lowest available wavelength. On the other hand inter-subnet lightpaths (those whose ingress and egress nodes are on different subnets or different rings for that matter) are assigned on the highest possible wavelengths. This way we have a static load balancing which also reduces the number of net transponder card type required in the ring [6]. We further assume that each ring network would have a two-fiber ring with half the channels in each fiber dedicated to shared path protection. For simplicity without loss of generality we assign even channels for work in the clock-wise fiber and odd channels for work in the counter-clockwise fiber. For lightpath establishment purpose we assume an optical service channel. As can be seen from Fig. 1. a WDM OADM guards the spectral contents of one subnet from the other. Hence to establish an inter-subnet lightpath (AE) the optical switch on that particular wavelength at the intermediate WDM OADM (node D) needs to be configured in the pass-through mode. The conventional service channel accomplishes this signaling procedure. So for lightpath AE, subnets 1 and 2 share the wavelength using the wavelength gateway node D. While establishing an intra-subnet lightpath IH, on say wavelength λ_1 the optical switch corresponding to λ_1 needs to be configured in the cross state. This ensures that λ_1 can be reused by subnets 1 and 2 internally (lightpaths GF, IH). In this way wavelength reuse is permissible. When a fiber cut occurs, protection is achieved by loop-back function of the ring.

III SIMULATION MODEL

We developed a simulation program to estimate the performance of both subnet based network as well as conventional WDM OADM network for similar traffic requirements. For a given number of nodes, based on the maximum traffic constraints the network was divided into subnets or sectors as per the algorithm. All intra-subnet traffic and inter-subnet traffic was assigned on wavelengths in ascending and descending order respectively. The routing and wavelength assignment algorithm used only shortest paths for both cases, while maximizing wavelength reuse. The reason we assume lightpaths on only shortest paths is to reduce Q-penalty including OSNR degradation. For inter-subnet lightpaths wavelength continuity is an important constraint. Future versions would include wavelength conversion at the wavelength gateway devices resulting in slightly better performance in blocking. We calculated the throughput, blocking probability and wavelength reuse factor for both the networks. A cost function assigned normalized cost to both the networks in terms of the number of

nodes and the components present at the nodes. From neutral vendor based calculations as well as the cost model provided in [3] a passive network element as demonstrated in [3] without transponders was roughly one-fourth the cost of a conventional WDM-OADM node. This cost model considered a conventional OADM network element to have full multiplex and de-multiplex sections in addition to amplifiers and switching fabric. The passive network element's cost analysis was done taking into account the passive devices and amplifiers mentioned in [4]. Both the network architectures required a pair of transponders for each source-destination pair to support lightpaths.
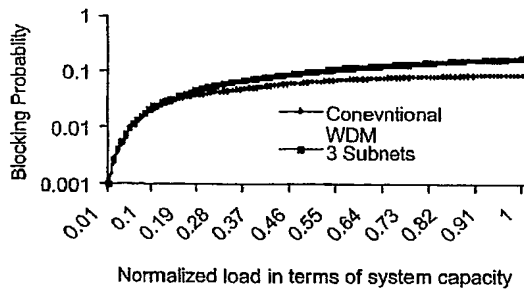

Normalized load in terms of system capacity

Fig. 2 Shows the blocking probability of a conventional WDM network and that of a subnet based network.
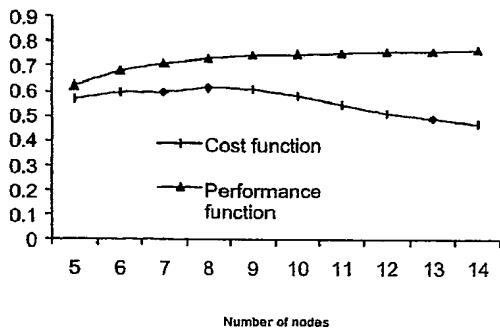

Number of nodes

Fig. 3 Shows the cost function and performance function of subnet network with respect to conventional WDM network for different nodal configurations.

The simulation algorithm performed extensive iterations with various configurations and load patterns. We were typically interested in configurations with number of nodes from 6-12, which were most widely deployed in metro networks. The number of subnets ranged from 1-4 with the 2-subnet and 3-subnet configuration generating most interest. Fig. 2 shows the blocking probability of a 3-subnet model compared to a conventional WDM OADM configuration for the same number of nodes (12 in this case). Due to the complete wavelength reuse available at each WDM OADM node the conventional WDM model performs slightly better in terms of blocking probability. The performance for low loads (<0.5) is almost the same, while for loads from 0.5-0.7 the performance is marginally better in

favor of the conventional network. The first passage time so critical in WDM networks is almost the same for both network types.

Fig. 3 shows the cost and performance functions of a subnet-based network in comparison to a conventional network. As can be seen performance in terms of throughput increases with the number of nodes (and hence subnets). The throughput of a subnet-based network is never less than 65 % of the throughput of a conventional network; however at the same time the cost is never greater than 60 % of the OADM network cost. In fact the cost decreases with number of nodes. The main factor to cost in subnet-based network is the transponder cards while the main factor responsible for cost in a conventional WDM network are the OADMs as well as the transponders. If we disassociate transponder cost from both networks we observed that the cost of subnet-based network is lesser than that of a conventional network by a factor of 3. Throughput performance of a subnet based network stabilizes between 78-88 % of conventional network for rings with 6<N<14. This result is also analytically verified in section III
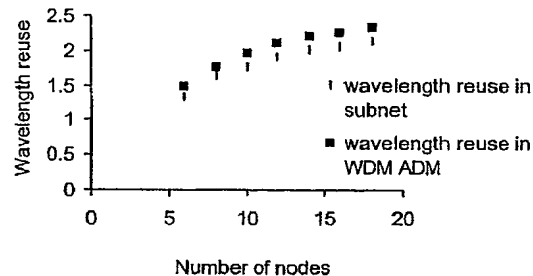

Number of nodes

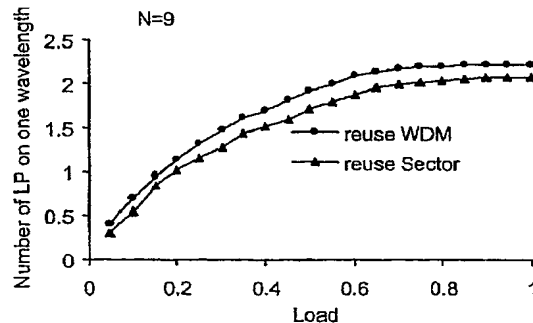Fig.4. Wavelength reuse as a function of number of nodes

Fig. 5. Wavelength reuse as a function of load

Fig. 4 and Fig. 5 show the wavelength reuse factor as a function of the number of nodes as well as load in both network types. Wavelength reuse factor is calculated as the average

number of lightpaths per wavelength in the network. The variation of wavelength reuse factor with number of nodes for both network types is also shown. The conventional network performs better by 10 %. This difference is minimal and can easily be discarded for systems having low-to-average loads. Also both networks have a similar response in terms of wavelength reuse.

IV COMPARISON WITH CONVENTIONAL NETWORK

The low cost subnet based network comprising of passive nodes divided by wavelength gateways performs almost as good as a conventional network. The main comparison characteristic for performance is the blocking of lightpaths which states the mean difference in throughput between the two networks. The total flexibility to reuse wavelengths in a conventional network allows it to carry more traffic than the subnet based network by a certain fraction.

This fractional difference between performances is quite minimal. Let the number of nodes within a given subnet be k, and let this subnet be named S. Consider a lightpath whose destination node is one of the k nodes in the subnet (Fig. 7). If the destination node was the kth node (which is a wavelength gateway device) we could reuse the same wavelength immediately, and the subnet system would perform equally as efficient as the conventional system. To estimate the difference in efficiency between a subnet system and a conventional system, we need to find the probability that an arbitrary lightpath would be destined for a node 1...k-1, for a particular subnet S but not node 'k' (wavelength gateway). The probability that a particular node within a subnet could be a destination node is 1/k. Further the probability that the destination node would be in subnet S is the probability of the subnet itself given by $\lambda_{max}/[(\acute{O}Tr_i)_{max}+\lambda_{max}]$. Thus the probability that the destination node would be 1...k-1 is given by

$$Pr(d = 1,2,3,...,k-1) = \frac{\lambda_{max}}{(\sum Tr_i)_{max} + \lambda_{max}}\left[1-\frac{1}{k}\right] \quad (1)$$

The probability in equation 1 compares the performances of conventional and subnet based networks in terms of blocking and throughput. Higher the probability of an intermediate node (other than a gateway) as a destination node, lower the efficiency of the subnet-based network as compared to a conventional WDM network. This result is verified through a simulation model (Fig. 6). The efficiency in terms of throughput of the system as compared to a conventional network is given by this probability expressed as a percentage.

Fig. 6 shows the comparative performance of a subnet-based network with conventional WDM OADM based network. The analytical as well as the simulated performance is shown. The simulation model assumes random lightpath requirements for various source-destination pairs. The efficiency is theoretically calculated using the analytical result in equation 1
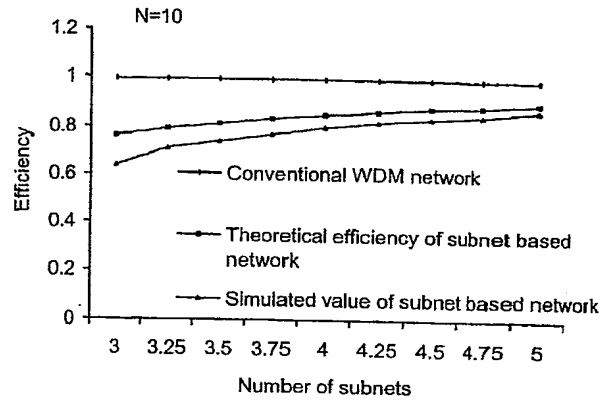

Fig. 6. Comparative analysis of WDM ADM based network and subnet-based network for theoretical and simulated values.
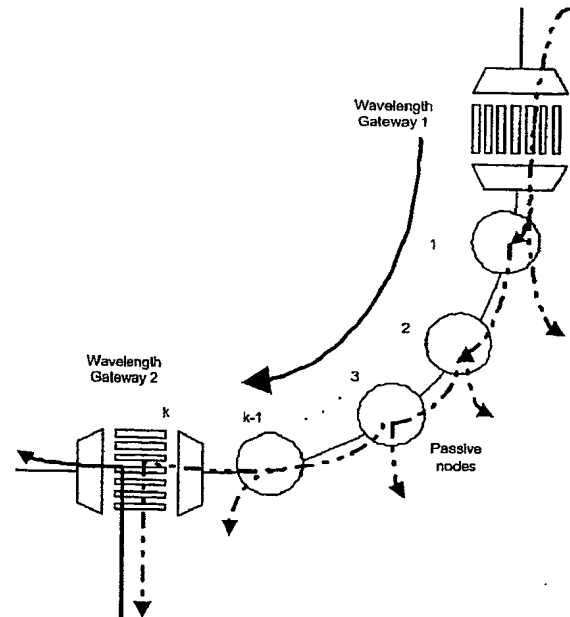

Fig. 7. The model used to perform analysis of inefficiency of subnet as compared to conventional network

V DISCUSSION

In this paper we have introduced the concept of optical subnets. Optical subnets in metro rings can insure system performance comparable with conventional WDM networks. For low-to-moderate loads the subnet system performance is at par with the conventional system, while the cost is always lesser than the latter. The subnet system utilizes the drawback in WDM

networks of multiple nodes providing pure transit (pass-through) function due to hop lengths greater than one hop. Using passive nodes divided by a few OADMs the network is a highly scalable and effective architecture in terms of performance. The analytical result for loss in efficiency between the two network architectures have been verified through simulation. For most networks the performance difference would not cross 10 % for low loads and 15 % for moderate loads. It is quite unlikely that rings would exploit the full load potential, and even if they do so, the difference in efficiency would not be greater than 25 %. At the same time there always would be a sizable cost reduction factor. Including transponder costs, the subnet configuration would conservatively save approximately 40-50 % of conventional network costs.

We have thus introduced a new class of hybrid networks for metropolitan area applications, which provides a cost effective and performance oriented solution for optical WDM networking

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